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Development of High Spectral Resolution Lidar System for Measuring Aerosol and Cloud

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A high spectral resolution lidar (HSRL) system based on injection-seeded Nd:YAG laser and iodine absorption filter has been developed for the quantitative measurement of aerosol and cloud. The laser frequency is stabilized at 80 MHz by a frequency locking system and the absorption line of iodine cell is selected at the 1111 line with 2 GHz width. The observations show that the HSRL can provide vertical profiles of particle extinction coefficient, backscattering coefficient and lidar ratio for cloud and aerosol up to 12 km altitude, simultaneously. For the measured cases, the lidar ratios are 10~20 sr for cloud, 28~37 sr for dust, and 58~70 sr for urban pollution aerosol. It reveals the potential of HSRL to distinguish the type of aerosol and cloud. Time series measurements are given and demonstrate that the HSRL has ability to continuously observe the aerosol and cloud for day and night.

Keywords : High spectral resolution lidar, Aerosol detection, Lidar ratio
OCIS codes : (280.0280) Remote sensing and sensors; (280.3640) Lidar; (280.1100) Aerosol detection

I. INTRODUCTION

Aerosol and cloud have significant impact on the radiation budget of the earth by scattering and absorbing solar radiation. Mie lidars are widely used for atmospheric measurements due to their simple construction and low laser requirements [1, 2]. However, the two unknowns, the backscattering and extinction coefficients of particles, in the Mie lidar equation cannot be resolved except by assuming the ratio of the two parameters [3]. Thus the Mie lidars are limited in quantitative measurements of atmospheric optical properties.

The elastic backscattered light received by lidars consists of a Mie scattering component from aerosol and cloud, and a Rayleigh scattering component from air molecules. For a narrow band laser, the Rayleigh scattering spectrum originated from molecules is broadened to more than 2 GHz for the thermal motion and collision of air molecules. It is much wider than the Mie scattering spectrum originated from particles since the motion of air molecules is much faster than that of particles. This suggests that a narrow band filter can be used to separate the two components. According to the above principle, high spectral resolution lidar (HSRL) using a narrow band laser and the high spectral resolution filter can measure the optical properties directly without additional assumptions [4, 5].

The HSRL system based on injection-seeded Nd:YAG laser and iodine absorption filter is developed by Anhui Institute of Optics and Fine Mechanics (AIOFM), Chinese Academy of Sciences (CAS) and is being used for tropospheric aerosol and cloud observations quantitatively and continuously.

II. PRINCIPLE OF HSRL MEASUREMENT

Iodine molecules have abundant absorption lines near 532 nm wavelength [6]. Taking into account the frequency range of Nd:YAG laser and the strength of absorption lines, the 1111 line (18788.4510 cm^{-1}) of iodine molecules

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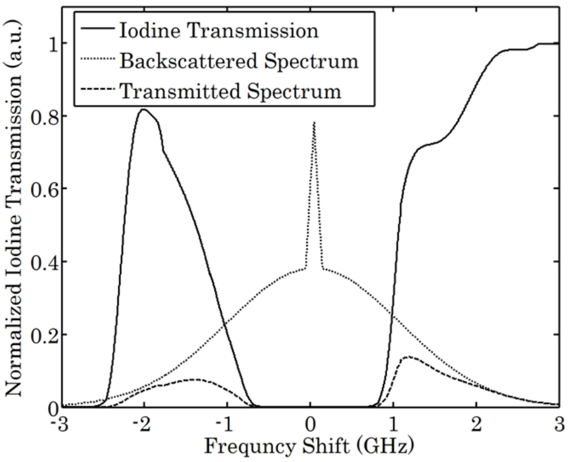

FIG. 1. Normalized transmission of iodine cell (solid line) together with the backscattered spectrum (dotted line) and the passed wings of Rayleigh spectrum (dashed line).

is chosen for our HSRL. The iodine spectrum has been measured with a wavelength meter by scanning the laser frequency. In the scanning process, a piezo element in the seed laser provides fast frequency tuning in a narrow-band and a thermoelectric cooler provides slow frequency tuning in a wide-band. With the iodine cell operating at 60℃, a high rejection up to 10^4 against the Mie signal can be obtained, and the wings of the Rayleigh spectrum can partly pass through the absorption filter, as shown in Fig. 1.

In practice, the signals received by telescope are split into two beams, one beam is sent through the iodine cell and detected by PMT as the molecular channel, and the other is detected directly as the total channel. Combined with the system calibration coefficients, the Rayleigh and Mie signals $N_{Mie}(z)$ and $N_{Ray}(z)$ can be retrieved, then the particle optical parameters can be deduced as follows :

$$\alpha_a(z) = -\frac{1}{2\Delta z}\ln\left[\frac{X_m\left(z+\frac{\Delta z}{2}\right)\Big/\beta_m\left(z+\frac{\Delta z}{2}\right)}{X_m\left(z-\frac{\Delta z}{2}\right)\Big/\beta_m\left(z-\frac{\Delta z}{2}\right)}\right] - \alpha_m(z) \quad (1)$$

$$SR(z) = \frac{N_{Mie}(z)}{N_{Ray}(z)} + 1 \quad (2)$$

$$\beta_a(z) = \beta_m(z)\cdot\left[SR(z) - 1\right] \quad (3)$$

$$LR(z) = \frac{\alpha_a(z)}{\beta_a(z)} \quad (4)$$

Where z is the altitude, $\alpha_a(z)$ is the particle extinction coefficient. $SR(z)$ and $\beta_a(z)$ are the particle backscatter ratio and backscattering coefficient. $X_m(z) = N_{Ray}(z) \times z^2$ is the range corrected Rayleigh signal, Δz is a range interval for calculation of gradient, $LR(z)$ is the lidar ratio, namely particle extinction to backscatter ratio. $\beta_m(z)$ and $\alpha_m(z)$ are the molecular backscattering and extinction coefficients which can be obtained from the measured temperature and pressure profiles or atmospheric model.

III. SYSTEM DESCRIPTION OF HSRL

The set up of HSRL system is shown in Fig. 2. A cw laser with about 40 mW at 1064 nm is injected into a Nd:YAG laser as the seed laser. A narrow pulsed laser at 532 nm is obtained after frequency doubling, and the spectral bandwidth is less than 90 MHz. The pulse energy of the transmitted laser is about 150 mJ at 30 Hz repetition rate, and the pulse duration is about 8 ns. Before transmission into air, the laser beam is collimated with a 3 times expander to improve the beam divergence. In the receiving unit, a Cassegrain telescope of 200 mm in diameter is used to collect the backscattered light. The received light is separated into two channels by a 1/4 beam splitter, the stronger beam is sent through a 20 cm long iodine cell and detected by PMT 1, the weaker beam is detected by PMT 2 directly. A 1-nm bandwidth filter and a lens are used before each PMT to suppress the background lights and to focus the beams. In operation, the iodine cell is thermally stabilized at 60℃, yielding the absorption up to 10^4 at the center of the 1111 line, and the line width is broadened to about 2 GHz. A transient recorder with 20 MHz sampling rate and 12 bit resolution is used in the HSRL for data acquisition.

In order to keep the laser frequency at the center of the iodine absorption line, a frequency locking system was developed as shown in Fig. 2 [7]. The system consists of two acousto-optic modulators (AOM) with 200 MHz acoustic frequency, a 10 cm iodine cell worked at 20℃ and two photo diodes (PD). In operation, a small portion of the transmitted laser is separated into the frequency locking system. By passing through two pinholes on a plate, the laser is restrained into two thin beams with 0.5 mm diameter. Then the two beams are separately transmitted into two AOMs. The two AOMs are mounted in slightly opposite deflections to produce the inverse frequency shifts on the first order beams. The zeroth order beams of AOMs that remains at the original frequency are trapped, while the first order beams with ±200 MHz frequency shifts are passed through the iodine cell and detected by PDs. When the frequency of the transmitted laser is turned to the center of the absorption line, the frequencies of their first order lights will shift to the symmetrical locations on the two sides of the absorption spectrum and the power ratio of the two detected beams will be a fixed value. Otherwise, the power ratio will change and the change can be feedback to guide the turning of the transmitted

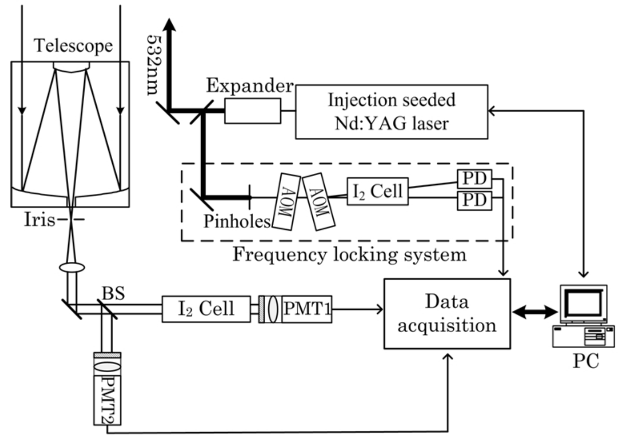

FIG. 2. Schematic diagram of the HSRL system.

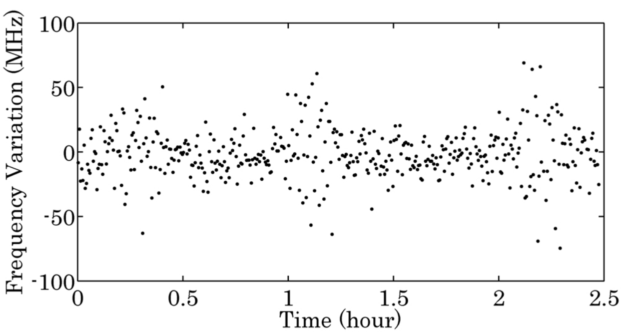

FIG. 3. Frequency variation of the transmitted laser for a 2.5 hours period. The standard deviation is 20 MHz.

laser frequency by adjusting the piezo voltage of the seed laser.

In order to verify the stability of the frequency locking system, the frequency variation of the transmitted laser is monitored during a period of 2.5 hours, as shown in Fig. 3. We can find that the frequency of the transmitted laser is locked in ±80 MHz for 2.5 hours and its standard deviation is 20 MHz. The stability of the transmitted laser frequency ensures the precision of HSRL system during the observation and makes it possible to realize the continuous and automatic measurement with HSRL.

IV. OBSERVATION RESULTS

Figure 4 gives the typical profiles of optical properties for cloud and aerosol cases observed by HSRL on the night of April 17, 2015. Figure 4(a) shows the range corrected signals of the total and molecular channels, simultaneously. Similar to the Mie lidars, the range corrected signal in the total channel (solid line) has layer structures. The two obvious layers indicate the aerosol existed below 3.2 km and cloud presented over 5 km. But the range corrected signal in the molecular channel (dashed line) is very smooth

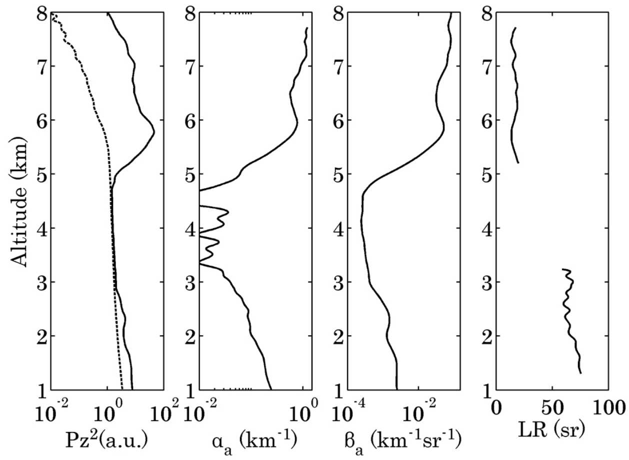

FIG. 4. Typical profiles of optical properties for cloud and aerosol cases measured with HSRL on April 17, 2015. (a) range corrected signals of total channel (solid line) and molecular channel (dashed line), (b) extinction coefficient, (c) backscattering coefficient, and (d) lidar ratio.

because the Mie scattering light induced by aerosol and cloud particles is absorbed by the iodine cell.

Based on the Eqs. (1) to (4), the vertical profiles of extinction coefficient, backscattering coefficient and lidar ratio of particles are derived and showed in Fig. 4(b) to (d). Because the extinction and backscattering coefficients correlate with the concentration of particles, their values decrease with the altitude below 3.2 km for aerosol and increase over 5 km for cloud. Both extinction and backscattering coefficients between 3.2 km and 5 km are very small, indicating the lower content of particles. The lidar ratio in this altitude cannot be obtained validly. Unlike the extinction and backscattering coefficients, the lidar ratios do not change evidently with altitude in each layer. The retrieved lidar ratios of aerosol particles below 3.2 km are 58~70 sr, and lidar ratios of cloud particles over 5 km are 14~20 sr. The reason is that the lidar ratio is an optical parameter, which depends on the physical properties of particles instead of the content of particles. So the lidar ratio measured by HSRL can be used to distinguish the types of particles.

Figure 5 shows the typical result of dust and aerosol particles below 3 km observed with HSRL on April 2, 2015. Two layers are obviously shown in Fig. 5(a) to (c) based on the structures of range corrected signals, extinction and backscattering coefficients. The lidar ratios are about 64 sr below 0.8 km and 28~37 sr over 1 km. The difference of lidar ratios in two layers demonstrates the different types of particles. According to the simultaneous observation of a polarization lidar nearby, the depolarization ratio of the lower layer and upper layer are 0.05 and 0.3 respectively. The larger depolarization ratio indicates the existence of nonspherical particles such as dust in the upper

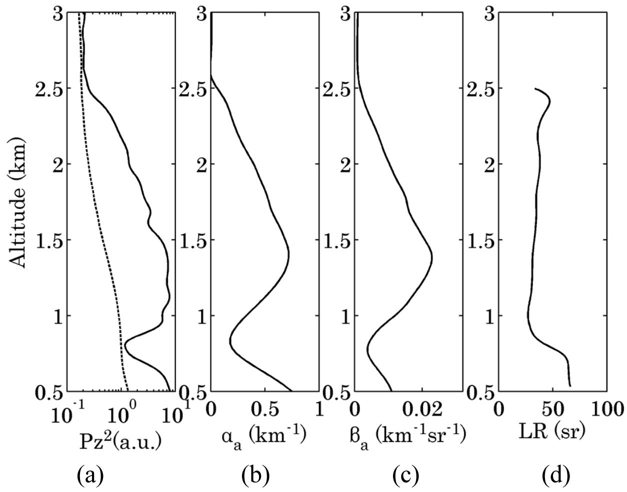

FIG. 5. Typical profiles of optical properties for dust and aerosol cases measured with HSRL on April 2, 2015. (a)-(d) are same parameters to Fig. 4.

layer, and the lower depolarization ratio denotes the spherical particles like urban pollution aerosol. Thus, the lidar ratios of urban pollution aerosol and dust measured by HSRL are about 64 sr and 28~37 sr, respectively.

To verify the ability of HSRL in continuous and automatic operation, we took a measurement from 09:20 to 22:00 on July 13, 2015. The temporal and vertical distributions of the extinction coefficients, backscattering coefficients and lidar ratios of aerosol and cloud particles during the experiment are showed in Fig. 6. The temporal resolution is 5 minutes and the range resolution is about 7.5 m. The detection altitude of derived extinction coefficient and lidar ratio at noon drops to about 3 km because of the dense aerosol in the boundary layer and the strong background from sun light, while the detection altitude rises up to 12 km at night. In the HSRL system, the Licel transient recorder is used for collecting return signals in the analog and photon counting detection chain, simultaneously. The combination of both signals gives the high linearity of the analog signal for strong signals and high sensitivity of the photon counting for weak signals. In order to avoid the influence of the overlap factor of the lidar system in near range, the bigger field of view is set in the receiver. It is helpful for measuring aerosol in near surface, but it is unable to restrict the strong solar background in daytime and is finally unable to get the valid photon counting data. Thus, the detection altitude in daytime is decreased for the only analog signals. In the next work, the larger expander in the transmitter and the receiver with the smaller field of view will be used to reduce the radiation from the sky background in daytime. In such case, both analog and photon counting signals will be observed and it makes it possible for lidar to increase the detection altitude up to 10 km at daytime. According to the extinction and back-scattering coefficients, a dense aerosol still exists below 2 km, and it gets thinner after 15:00. Its extinction coefficient ranges from 0.1 to 0.8 km^{-1}. Another aerosol layer at 3 km and a cloud layer over 9 km are presented after 18:00 and 20:00, respectively. The extinction coefficient of the upper aerosol layer is about 0.2 km^{-1} on average and the values for cloud layer vary from 0.2 to 0.6 km^{-1}. The retrieved lidar ratios of two aerosol layers are 40~50 sr, indicating they have similar physical properties. The lidar ratios of the cloud layer are obviously smaller than aerosol layers and are about 10~20 sr. The results above suggest that the continuous observation with HSRL not only provide the vivid temporal and vertical views of structure and concentration of aerosol and cloud, but also give the information of their types.

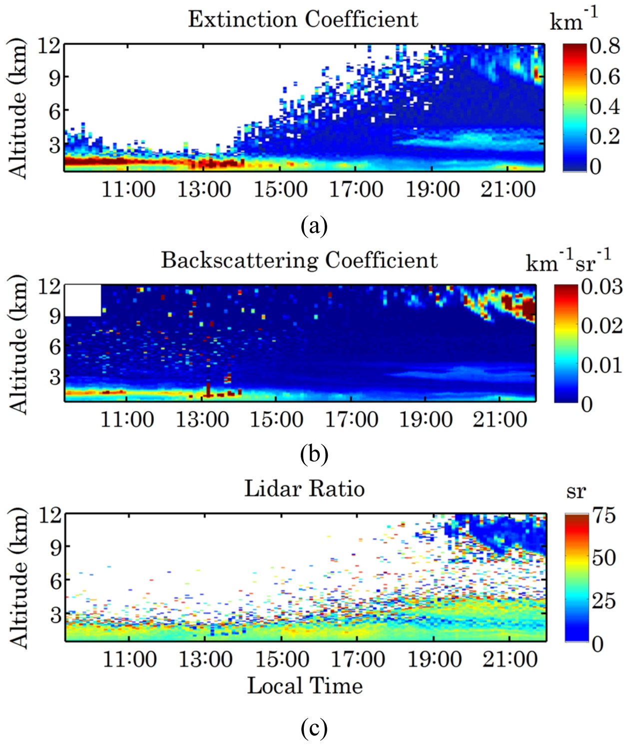

FIG. 6. Continuous results of particle optical properties observed by HSRL from 09:20 to 22:00 on July 13, 2015. (a) extinction coefficients, (b) backscattering coefficients, and (c) lidar ratios of particles.

V. CONCLUSION

In conclusion, an HSRL system based on injection-seeded Nd:YAG laser and iodine absorption filter has been developed for the quantitative measurement of aerosol and cloud. Unlike the traditional Mie lidar, the extinction coefficient, backscattering coefficient and lidar ratio are derived independently without any assumption. The typical results demonstrate that HSRL is a useful tool to obtain the information of both the contents and types of aerosols and clouds. Due to the affect of strong background light, the valid altitude of HSRL is limited in the boundary layer at noon. Some works such as the smaller field of view and the narrow background-removing filter will be actualized in the HSRL system.

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